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A Self-diagnostic Method for the Electrode Adhesion of an Electromagnetic Flow-meter

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Abstract: Electrodes of electromagnetic flow-meter are subject to contamination in sewage measurement. In this paper, the relationship between the internal resistance of the flow-induced voltage and the electrode contamination is analyzed on the basis of numerical analysis. A new self-diagnostic method for electrode adhesion with additional excitation based on photovoltaic cell is proposed, in which magnetic excitation for flow-rate measurement and electric excitation for electrode self-diagnosis is divided in both time domain and frequency domain. A dual-excited electromagnetic flow-meter with electrode self-diagnosis was designed and validated. Simulation experiments based on the change of the internal resistance of the flow-induced voltage were carried out. And the experimental results fully show that this new method is feasible and promising. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Electrode adhesion self-diagnosis, Electromagnetic flow-meter, Dual excitation, Photovoltaic cell.

1. Introduction

Electromagnetic flow-meter is widely used in sewage measurement for its smooth meter pipe, high accuracy, wide turndown ratio, etc. However, the transducer of the flow-meter, especially the inner electrode, is subject to fouling in such severe ambient. The assumption that wetted electrode resistance between the electrode and the fluid ground is uniform will never be justified due to electrode fouling, and the response of the flow-meter will not be accurate [1]. It also may be impractical for an installed electromagnetic flow-meter to be removed for calibration. Therefore, real-time electrode adhesion self-diagnosis in situ, to identify whether the performance of the electromagnetic flow-meter is affected by contamination, has been of great concern by experts and scholars in recent years [2].

At present, there are mainly two ways for electrode adhesion self diagnosis in situ. One is to measure the level of the industrial frequency noise which is imposed on the flow rate signal. But it is hard to judge electrode adhesion correctly because the noise is much sensitive to environmental factors. The other is named as additional electric excitation method [3], that is, with additional higher frequency electric excitation (usually under 2 kHz [4-6]), the change on the surface of the measuring electrode can be detected on the basis of at least one impedance value measured between measuring electrode and reference potential [5]. Generally, the electric excitation source was used in parallel with the measurement loop [3-9]. However, the excitation source has the same ground with the measuring amplifier, so that the amplifier equivalent input impedance will be reduced and the velocity signal may be in partial loss. Yet if the excitation source was in series between the electrode and the amplifier, the complicated electrical characteristics may introduce serious electromagnetic interference. So both the design of excitation source and the connection method are crucial for this electric excitation method.

Based on our previous studies of dual-excited electromagnetic flow-meters [3, 8-11], this paper proposed a new dual-excited electromagnetic flow-meter, with electrical excitation source based on photovoltaic cells in series with the primary measurement loops. This method ensures excellent flow-rate measurement with no reduction in the equivalent input impedance of the instrumentation amplifier theoretically. And it also provides an easy way to control the electric-excited module, minimizing the interference from the outside. On the basis of numerical analysis for the electrode adhesion of an electromagnetic flow-meter, this paper firstly presented a model for the transducer of an electromagnetic flow-meter with electrode adhesion. Then, a new dual-excited electromagnetic flow-meter based on photovoltaic (PV) cell [12] was designed and validated. From two aspects of the electromagnetic flow-meter performance (the measurement precision and the zero stability), simulation experiments based on both resistors and entities were carried out.

2. Numerical Analysis for Electrode Adhesion of an Electromagnetic Flow-meter

The finite element analysis with the software of ANSYS was used to obtain the virtual voltage between the pair of sensing electrodes with unit virtual current excitation. And the virtual voltage reflects the equivalent resistance between those electrodes. A 3-D numerical model (Fig. 1) for an electromagnetic flow-meter with electrode fouling was built with SOLID231 electric elements.

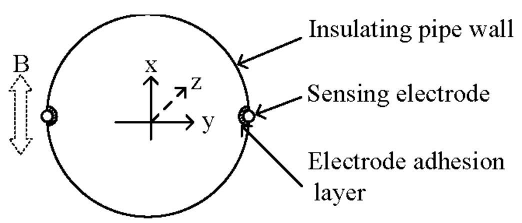

Fig. 1. Numerical Model for the electromagnetic flow-meter with electrode fouling. B denotes the magnetic field.

Its pipe diameter was 100 mm, and overall length was 260 mm. The pair of electrodes, whose surface diameter 10 mm and maxim thickness 2 mm were both coated with an adhesion layer of special thickness and resistivity. The electrode was seen as a conductor. The boundary condition on the insulating pipe wall, apart from the electrodes, was taken as $\partial u/\partial r=0$, and the one for the two ends of the flow-meter pipe was taken as U=0 to simulate earthed metal pipes. Unit current entered the meter through one electrode and left through the other. The virtual voltage could be obtained from the Laplace equation $\nabla^2 U = 0$.

The numerical solution (Fig. 2) clearly shows that the virtual voltage, i.e. the equivalent resistance between the pair of electrodes, increases with the thickness and the resistivity of the electrode adhesive layer. It should be noted that those resistivity and thickness of the electrode adhesion layer, which will cause any change of weight function, are not involved in this paper.

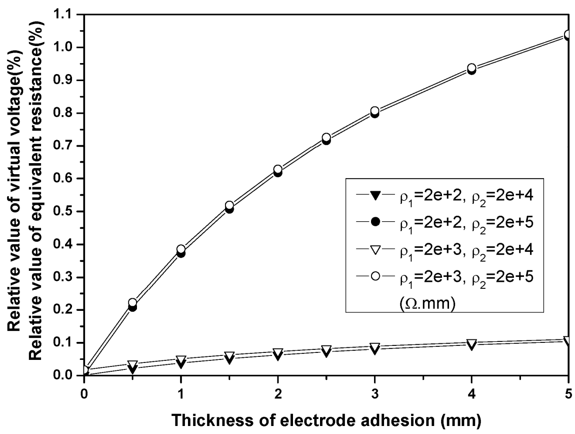

Fig. 2. Virtual voltage (equivalent resistance) between two sensing electrodes versus thickness of electrode adhesion.

In Fig. 2 ρ_1 denotes the resistivity of fluid, whilst ρ_2 denotes that of electrode adhesion layer.

3. Principle

According to the above numerical solution, this paper translates electrode fouling into the change in wetted electrode resistance. And the key to electrode adhesion self-diagnosis is to measure the wetted electrode resistance for judging whether the performance of the electromagnetic flow-meter is affected.

A model of the electromagnetic flow-meter transducer with electrode fouling (Fig. 3) is presented, where wetted electrode resistance R_{01} and R_{02} consist of both liquid inherent resistance r_s and equivalent resistance r_{01} or r_{02} related to the level of electrode fouling. And the change of the wetted electrode resistance affected the performance of the electromagnetic flow-meter mainly in two aspects, one is that the asymmetry of r_{01} and r_{02} will affect zero stability, the other is that the increase of r_{01} and r_{02} will lower measurement accuracy. As a circuit model of electrode measurement loop shown in Fig. 4, the output voltage can be given by

$$V_{out} = K_m \times E_0 \times \frac{R_i}{R_{01} + R_{02} + R_i}, \quad (1)$$

where K_m is the amplification coefficient of the instrumentation amplifier, E_0 is the flow-induced voltage, R_i is the equivalent input resistance of the amplifier. From Eq. 1, the rate of signal attenuation can be calculated by

$$\alpha = \frac{R_{01} + R_{02}}{R_{01} + R_{02} + R_i} \times 100\%, \quad (2)$$

It is obvious that the increase of $R_{01}+R_{02}$ due to electrode contamination will result in higher α and lower measurement accuracy of the device. To keep the measurement accuracy higher than 1 ‰, for example, α must be less than 1 ‰, and $R_{01}+R_{02}$ should be less than $R_i/999$.

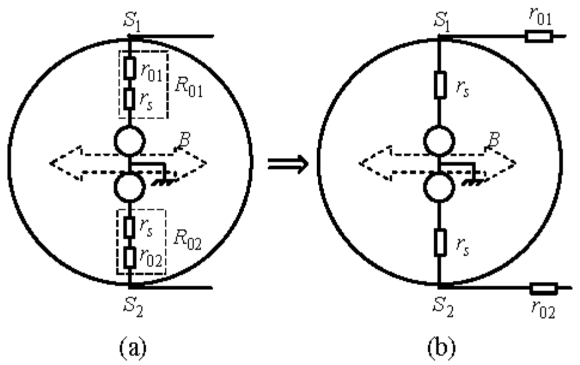

Fig. 3. A model of the electromagnetic flow-meter transducer with electrode fouling. Model (a) can be equivalent to model (b).

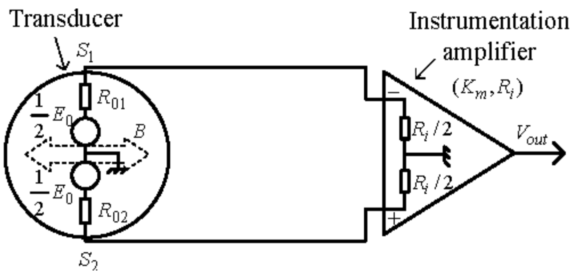

Fig. 4. A model of measurement loop. B denotes the magnetic field.

The principle block diagram of a dual-excited electromagnetic flow-meter based on PV Cell is illustrated in Fig. 5. It consists of a pair of sensing electrodes, a pair of PV converters and an instrumentation amplifier. Each PV converter can be regarded as a voltage source, which composes of a PV Cell and a resistor, activated by an adjacent led controlled with the digital to analog converter (DAC) of the Micro Control Unit (MCU). E_a and E_b is the voltage generated by the two PV converters, whilst R_a and R_b is their serial resistor respectively. In order to being distinguished from the role of magnetic excitation, it is called electric excitation when E_a and E_b are generated. Moreover, each input end of the instrumentation amplifier is parallel with a capacitance C_0, which leads to different equivalent input impedance of the amplifier with different frequency of the input signal for magnetic excitation and electric excitation. Provided that $E_p=E_a+E_b$ and $R_p=R_a+R_b$, the output of the instrumentation amplifier can be given by

$$V_{out} = K_m \times \frac{R_i}{R_{01} + R_{02} + R_p + R_i} \times (E_0 + E_p), \quad (3)$$

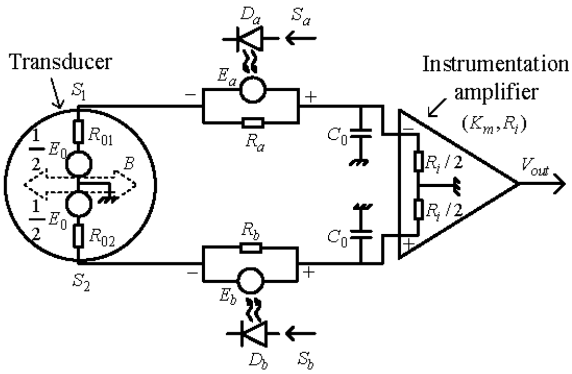

Fig. 5. Principle block diagram of a dual-excited electromagnetic flow-meter based on PV Cell.

In each measuring cycle, magnetic excitation alternates with electric excitation (Fig. 6). During the period of magnetic excitation, $E_p = 0$. The effect of C_0 can be ignored due to low magnetic excitation frequency. According to the Faraday law of magnetic induction [13], $E_0 = K_0 \times B \times D \times V$, where K_0 is the coefficient of the flow-meter, B is the magnetic flux density, D is the pipe diameter. Substituting it into Eq. 3, the corresponding flow rate can be calculated by

$$V = \frac{V_{out}}{K_m \times K_0 \times \mathrm{B} \times \mathrm{D}} \times \frac{R_{01} + R_{02} + R_p + R_i}{R_i}, \quad (4)$$

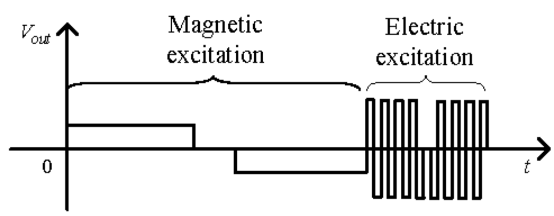

Fig. 6. Illustration of time share of dual excitation in one measuring cycle. t denotes the time, and V_{out} denotes the output voltage of the measuring loop.

During the period of electric excitation, $E_0=0$. However, R_i is more than 400 MΩ whilst R_{01} and R_{02} are smaller than 200 kΩ in general. Compared with the large equivalent input resistance R_i , the change of R_{01} and R_{02} are too faint to make any appreciable change of V_{out}. To measure the resistance $R_{01}+ R_{02}$ well, the equivalent input impedance of the instrumentation amplifier Z_{eq} should be reduced to the same order as $R_{01}+ R_{02}$. $Z_{eq} = R_i//Z_C$, where Z_C is the impedance of C_0. The resistance $R_{01}+ R_{02}$ can be calculated by

$$R_{01} + R_{02} = \frac{K_m \times E_p \times Z_{eq}}{V_{out}} - R_p - Z_{eq}, \quad (5)$$

In this research, each entire measurement cycle is approximately 360 ms, in which 40 ms is for resistance $R_{01}+ R_{02}$ measurement with 2 kHz square wave electric excitation. When AD620 is chosen as the instrumentation amplifier, 470 pF of C_0 is a perfect choice.

4. Experimental Results

In order to validate the new self-diagnostic approach for the electrode adhesion of an electromagnetic flow-meter, three experiments were carried out, including:

1) Experiment for electric-excited module;

2) Simulation experiment for electrode adhesion self-diagnosis based on both resistors and entities;

3) Simulation experiment for zero stability.

Experiment (1) tested the pair of PV converters for electric excitation. Si photodiode S1133-01, the PV cell in this research, was in the charge of a red led which was dominated by the DAC of the microcontroller. The value of DAC ranged from 0 to 4096, whilst the voltage generated by the PV converter ranged from 0 to 120 mV. The experimental result shows that PV Cell is controllable and stable. And it would be better when the excitation frequency is lower than 10 kHz and the peak to peak value of the excitation voltage is higher than 10 mV. And the excitation voltage of about 42 mV was selected for experiment (2) and (3).

It is very difficult to build a practical environment of electrode fouling for test. Simulation experiments based on both resistors and entities validated the function of electrode adhesion self-diagnosis.

4.1. Simulation Experiment for Electrode Adhesion Self-diagnosis Based on Resistors

This experiment was conducted with a circuit model as shown in Fig. 7. It was performed in two ways. In dual-ends simulation, R_{01} and R_{02} were always chosen the same value. In single-end simulation, one resistor kept at a definite value, and the other one changed.

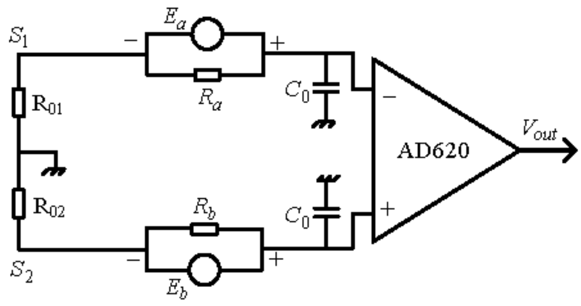

Fig. 7. Circuit model of simulation experiment for electrode adhesion self-diagnosis.

Table 1 shows the main experimental results. Variation of V_{P-P} with R_{01} and R_{02} is shown in Fig. 8. V_{P-P} is corresponding to the peak-to-peak value of the electric excitation square wave, with V_{out} filtered by a band-pass filter and amplified, captured by the analog to digital converter of MCU. α is calculated according to Eq. 2, provided that the input resistance of the instrumentation amplifier is 400 MΩ as usual. In Table 1, the left set is the result of dual-ends simulation experiment, whilst the right one is the result of single-end simulation. It should be noted that the experimental result was similar when R_{01} kept at a definite value and R_{02} varied in single-end simulation.

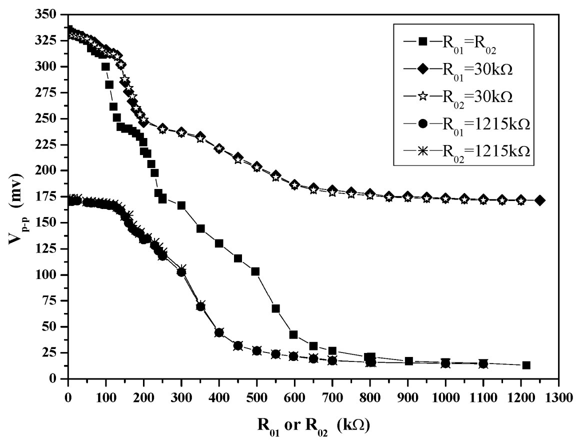

Fig. 8. Variation of V_{P-P} with R_{01} and R_{02} for simulation experiment based on resistors.

One can see that the increase of R_{01} and R_{02} results in obvious attenuation of V_{P-P}. As shown in Table 1, when R_{01} and R_{02} were 200 kΩ, α was 1 ‰ and V_{P-P} arrived at 223 mV. The measurement accuracy will not match the standard demand if both R_{01} and R_{02} further increase. Similarly, in single-end simulation, when α was bigger than 1 ‰, V_{P-P} was always smaller than 223 mV. Consequently, checking whether V_{P-P} is bigger than 223 mV can be used to keep the measurement accuracy of the electromagnetic flow-meter higher than 1 ‰ in this research.

Table 1. Relationship between V_{P-P} and both R_{01} and R_{02} in simulation experiment based on resistors.

$R_{01}=R_{02}$				R_{01} or R_{02}=30kΩ				R_{01} or R_{02}=1215 kΩ			
R_{01}(kΩ)	**R_{02}(kΩ)**	**V_{P-P}(mV)**	**α (‰)**	**R_{01}(kΩ)**	**R_{02}(kΩ)**	**V_{P-P} (mV)**	**α(‰)**	**R_{01}(kΩ)**	**R_{02}(kΩ)**	**V_{P-P} (mV)**	**α(‰)**
10	10	333	0.05	50	30	327	0.20	10	1215	173	3.06
30	30	330	0.15	100	30	314	0.33	151	1215	157	3.42
50	50	325	0.25	200	30	249	0.58	200	1215	135	3.54
99	99	300	0.50	250	30	240	0.70	300	1215	106	3.79
151	151	241	0.76	**400**	**30**	**221**	**1.08**	351	1215	71	3.92
200	**200**	**223**	**1.00**	600	30	186	1.58	400	1215	45	4.04
229	229	198	1.15	1000	30	173	2.58	597	1215	22	4.53
239	239	178	1.20	1200	30	171	3.08	1000	1215	15	5.54
250	250	172	1.25	30	50	326	0.20	1215	10	170	3.06
300	300	167	1.50	30	100	316	0.33	1215	151	156	3.42
351	351	144	1.76	30	200	247	0.58	1215	200	134	3.54
400	400	130	2.00	30	250	241	0.70	1215	300	103	3.79
496	496	103	2.48	30	400	221	1.08	1215	351	69	3.92
597	597	42	2.99	30	600	187	1.58	1215	400	44	4.04
1000	1000	16	5.00	30	1000	174	2.58	1215	597	22	4.53
1215	1215	13	6.07	30	1200	172	3.08	1215	1000	15	5.54

4.2. Simulation Experiment for Electrode Adhesion Self-diagnosis Based on Entities

This simulation experiment was carried out with an electromagnetic flow-meter whose nominal diameter is 100 mm in vertical with bottom sealed. And electric insulation tape, transparent adhesive tape, hot melt adhesive and chewing gum were used as dirt on the electrodes. For each test, the electrodes were cleaned before covered with dirt entity entirely as fouled.

Table 2 shows the experimental results. The value of R_{01} and R_{02} are equivalent calculated according to the results of simulation experiment based on resistors.

Table 2. Relationship of entity to valid signal V_{P-P} in simulation experiment based on entities. Case 1: both electrodes clean; Case 2: one electrode clean, the other one fouled; Case3: both electrodes fouled.

Condition	Entity type	V_{P-P} (mV)	R_{01} (kΩ)	R_{02} (kΩ)	α (‰)
Case 1	Hollow pipe	133	391	391	1.96
	Full pipe	330	30	30	0.15
Case 2	Electric insulation tape	171	30	1215	3.11
	Electric insulation tape	168	1215	30	3.11
	Transparent adhesive tape	168	1215	30	3.11
	Transparent adhesive tape	168	30	1215	3.11
	Chewing gum	241	244	30	0.69
	Chewing gum	242	30	239	0.67
Case 3	Eectric insulation tape	143	356	356	1.78
	Transparent adhesive tape	143	356	356	1.78
	Chewing gum	192	232	232	1.16

Obviously, when the clean electrodes immersed in full pipe, the equivalent contact resistance is about 30 kΩ whilst the one for hollow pipe is about 390 kΩ. For one electrode clean, dirt entities such as electric insulation tape, transparent adhesive tape or hot melt adhesive fouled on the other electrode could be checked well. And the metros chewing gum fouled one electrode resulted in lesser signal attenuation. When both electrodes fouled with the above three dirt entities, signal attenuation was measured as a bit serious.

4.3. Simulation Experiment for Zero Stability

Experiment (3) for zero stability was carried out in a flow test rig. It was conducted with a circuit model as shown in Fig. 9. Electrode adhesion was simulated by resistor r_{01} and r_{02} in series with the measurement loop, where r_{01} simulated the electrode adhesion on electrode S_1, and that r_{02} simulated the one on electrode S_2. Resistors both r_{01} and r_{02} ranged from zero to 200 kΩ, where the value of zero meant the corresponding electrode never fouled.

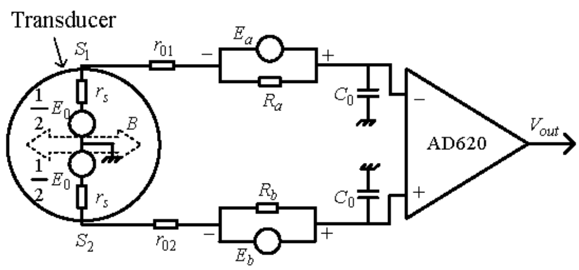

Fig. 9. Circuit model of simulation experiment for zero stability.

Table 3 shows the experimental results. Zero point would change little when r_{01} and r_{02} kept the same. But when only one resistor increased and the other kept at zero, zero point would shift evidently. The reason is that larger the resistor is, more serious the noises, in particular the power line interference, are imported. Especially when the electrode impedance mismatches, common mode interference could not be rejected effectively by the instrumentation amplifier. As a result, it is a challenge for the performance of the electromagnetic flow-meter.

Table 3. Zero point and V_{P-P} versus resistors both r_{01} and r_{02} in experiment for zero stability with electrode contamination simulated. V_{P-P} denotes the level of electrode adhesion measured during electric excitation.

r_{01}, (kΩ)	r_{02}, (kΩ)	Zero point (mm/s)	V_{P-P} (mV)
0	0	1.4~ 1.9	330
15	15	1.1~ 1.8	324.1
39	39	0.1~ 0.8	314.5
100	100	-0.8~ -1.9	273.6
200	200	-5.8~ -7.5	203.1
15	0	0.2~ 0.8	325.8
39	0	-1.3~ -1.9	320
100	0	-6.6~ -7.3	298.8
200	0	-16.4~ -18.2	251.4
0	15	2.3~ 2.9	326.2
0	39	3.6~ 4.3	320.4
0	100	7.1~ 8.6	299.3
0	200	12.4~ 13.2	253.3

5. Conclusion

A model for electrode adhesion, a new approach for electrode adhesion self-diagnosis, and a dual-excited electromagnetic flow-meter based on PV Cell are presented in this paper. Experiment for electric-excited module showed that the electric excitation source based on PV Cell could be easily controlled with no further noises imported. Simulation experiment for electrode adhesion self-diagnosis based on resistors and entities showed that electrode contamination could be identified effectively with this new approach. And experiment for zero stability where electrode adhesion simulated with resistors showed that zero offset increased with the level of the electrode impedance mismatched. The analysis of experimental results is based on the assumption that the instrumentation amplifier input resistance is 400 MΩ, which is somewhat different in field.

Further study and experiments for electrode fouling is needed to validate this novel approach. Nonetheless, the present experimental results fully proved that this new approach is effective and promising.

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